Effect of Section Thickness on Fatigue Performance of Laser Sintered Nylon 12

Hoda Amel[1,a], Jem Rongong[1], Hadi Moztarzadeh[2], Neil Hopkinson[1*]

1. Department of Mechanical Engineering, Faculty of Engineering, Mappin St, Sheffield, UK

2. Warwick Manufacturing Group, University of Warwick, Coventry, United Kingdom

* Present Address: Xaar plc, 316 Cambridge Science Park, Milton Rd, Cambridge, United Kingdom

a. Corresponding author, hoda.amel@gmail.com, 07908479413

Abstract

Laser Sintering offers manufacturers freedom of design, which enables creating parts with complex geometries. However, very little investigation has been made into the effects of geometry on mechanical properties of the parts. In the present study, Laser Sintered Nylon 12 parts with different section-thickness are subjected to displacement-controlled tension-tension and force-controlled fully-reversed fatigue loading to investigate the effect of geometry on their fatigue behaviour. Section-thickness of the parts is shown to have no significant influence on the fatigue behaviour under tension-only loading. However, fatigue life of parts under fully-reversed loading is shown to increase with section thickness.

Keywords: Laser Sintering, Polymer, Additive Manufacturing, Fatigue, Cyclic loading

1. Introduction

Additive Manufacturing (AM) technologies have long been renowned for producing parts with poor and/or unrepeatable mechanical properties. As AM of end-use components becomes increasingly viable, the ability to produce parts with repeatable and predictable mechanical properties has become progressively more important.

Laser sintering (LS) is an AM process which generates complex 3D parts by sintering powder particles in a layer by layer basis using a CO_2 laser. Parts produced by LS have been shown in several studies [1]–[4] to demonstrate mechanical properties that are very close to the material properties obtained by conventional manufacturing processes, like injection moulded plastic components.

Fatigue behaviour of polymer LS parts has been scarcely studied previously and no fatigue information can be found in manufacturers' data sheets. In a study by Blattmeier et al [5] laser sintered specimens made of a polyamide powder (with 60% used and 40% virgin powder) with treated (with surface finishing) and non-treated surfaces were employed to examine surface influence on their fatigue behaviour in a load increase method. Van Hooreweder et al [6] subjected Nylon 12 laser sintered specimens to stress-controlled tension-compression fatigue loading with zero mean stress to investigate their thermal and microstructural response. Amel et al. [7] investigated fatigue behaviour of LS Nylon 12 parts subject to displacement-controlled tension only fatigue loading. In a recent study, Van Hooreweder et al [8] have explored the difference in fatigue behaviour of LS and injection moulded Nylon 12 samples.

Several factors, both internal and external, have been identified as parameters that could influence cyclic performance and fatigue life of polymers[9]–[11]. Therefore, any parameter that is considered likely to affect the internal structure of the polymer parts might influence the cyclic performance as well. Also, Structural properties of the polymers such as molecular weight and degree of crystallinity, are influenced by the manufacturing process and parameters associated with it [12].

One of the distinctive advantages of LS is the freedom of design offered by this technique, which enables optimisation and design options leading to creating parts with complex geometries. However, very little investigation has been made into the effects of geometry on the mechanical properties of the parts [13]. Datasheet values reported by manufacturers for many commonly required properties are only for standard specimen sizes. It has been suggested that properties of parts with varying section-thicknesses might be different due to different thermal conditions they experience during manufacturing, which may ultimately lead to different molecular parameters.

The aim of the present study was to investigate the effect of section thickness on fatigue performance of LS Nylon 12 parts subject to tension-tension and tension compression cyclic loading.

2. Method and Materials

Three sets of tensile test specimens with section thicknesses of 2mm, 4mm and 6mm, were designed. As different specimen thicknesses were chosen, standard specimen geometries had to be altered so that the same geometry could be employed for both sets of experiments. Calculations based on the Young's modulus and buckling analysis combined with machine loading capabilities resulted in the sample geometry shown in Figure 1.

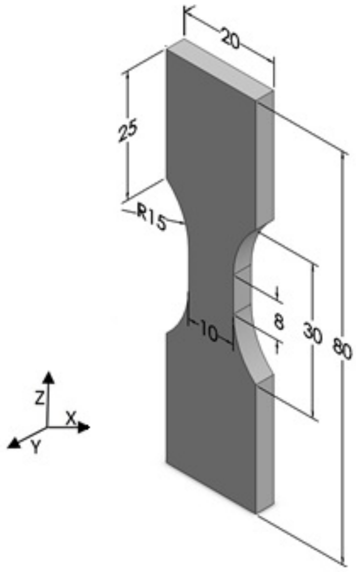


Figure 1- Dimensions of the test specimens (all dimensions in mm)

All specimens were manufactured in "one-build" of a CO_2-laser EOS P100 laser sintering machine to eliminate the possible difference in build conditions of different runs. Mixed EOS PA2200 (50% virgin, 50% used) as used by industry, otherwise known as Nylon-12 was used to manufacture the parts. Parts were built along the (z) direction with their long axis perpendicular to the build platform as shown in Figure 1, so that they would be loaded in their most critical direction and were all manufactured in one horizontal plane. Standard machine parameters, as shown in Table 1, were used for manufacturing of the parts.

Table 1- Standard machine parameters

Process Chamber Temperature	170°C
Laser Power	21W
Speed	2500mm/s
Layer Thickness	0.1mm
Laser Beam Diameter	0.43mm

Physical properties of the samples were measured prior to testing. Samples were weighed using a laboratory scale. Height, Width, and Cross sectional dimensions of the gauge area of the samples were measured using Vernier Callipers. Surface roughness of the samples was measured using a Surftest column type apparatus. A measuring probe with radius of 1µm was used to scan a straight track of 30mm in the longitudinal direction at 0.5mm/s and average surface roughness (R_a) was recorded. Special care was taken to limit the measurement force.

All mechanical tests were performed using an MTS 858 Table Top System, capable of applying both static and dynamic loads. Specimens were fixed in the machine using wedge grips. 6 samples of each section thickness were employed for tension-tension and 5 samples for tension-compression tests. Tests were carried out at room temperature (26°C). The surface temperature of the specimens was measured using a Micro-epsilon ThermoIMAGER infrared camera.

2.1. Tension-Tension Excitation

For tension-tension tests, displacement-controlled cyclic loading was applied to the specimens; the maximum peaks of which were selected as 80% of deflection at break for the parts (1.8mm) and the minimum peak was selected in order to avoid inducing compression in the specimens (1mm), and the required force was recorded. The frequency of loading was set as 2Hz to prevent hysteresis heating of the samples.

2.2. Tension-Compression Excitation

For tension-compression tests, a force-controlled tension-compression cyclic load was applied to the 4mm and 6mm samples at room temperature with a frequency of 2Hz. The 2mm samples buckled under tension-compression loading within a few cycles because the drop in modulus caused by the rapid temperature rise reduced the critical buckling load. Force-controlled loading was chosen as all parts buckled under displacement-control. This load was applied in a fully reversed form (R=-1), so zero mean stress was incurred. Samples were tested at two stress levels of 20MPa and 30MPa to provide a reasonable time to failure (Ultimate Tensile Strength of the samples was measured as ~48MPa).

3. Results and Discussion

3.1. Tension-Tension Excitation

In order to investigate the effect of section thickness of the samples on their tension-tension fatigue life, number of cycles to failure of each sample was plotted against their section thickness for the examined displacement level as shown in Figure 2.

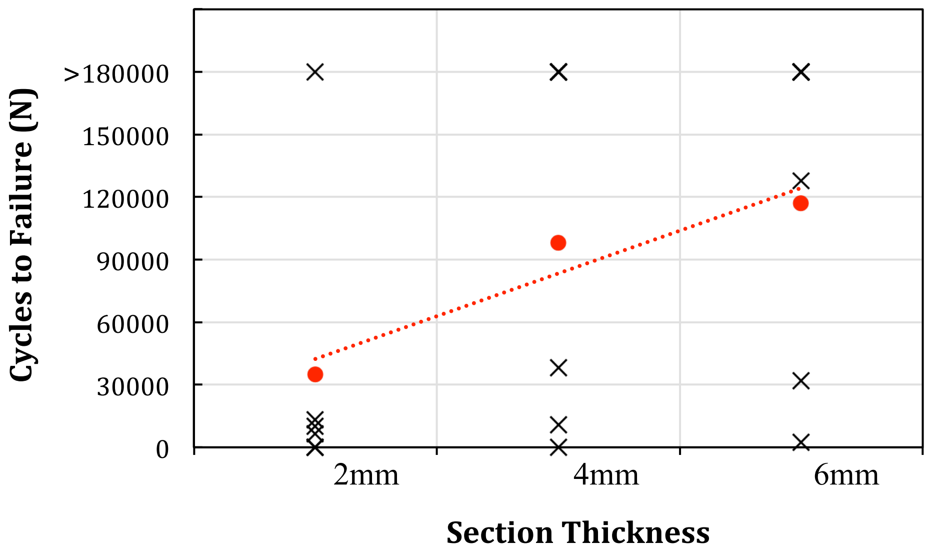


Figure 2- Fatigue life of samples with different section thicknesses under displacement-controlled tension-tension loading (max displacement=1.8mm, amplitude=0.4mm)

In order to examine the statistical significance of the differences observed between the three groups of section-thicknesses, non-parametric Kruskal-Wallis test was performed on the obtained values of fatigue life in all the samples in SPSS, considering the maximum life time of unbroken samples to be 180000. The result suggests that the distribution of fatigue life data is the same across the three section thicknesses. In other words no statistical significance exists between the fatigue lives of different section thicknesses.

In a previous study by the authors [7], it was shown that applying the same test conditions on specimens with the same section-thickness that were built with the same machine parameters can result in very different values for fatigue life, which shows the variable nature of this material under tension-tension cyclic loading.

Fatigue life for all three section-thicknesses is plotted against density and surface roughness in Figure 3 to investigate possible correlations. It should be noted that in order to find a trend line for the results, the maximum fatigue life has been considered as 180000 cycles. As can be observed from the graphs, most of the R-squared values are smaller than 0.1, which confirms that fatigue life of 2mm and 4mm samples is independent of their densities and surface roughness and fatigue life of 6mm samples is independent of their surface roughness.

However, a closer fit seems to exist between fatigue life of the 6mm samples and their densities. It can be presumed from the results that although fatigue life of samples with different section thicknesses is not significantly different, its dependence leans more towards density as samples become thicker.

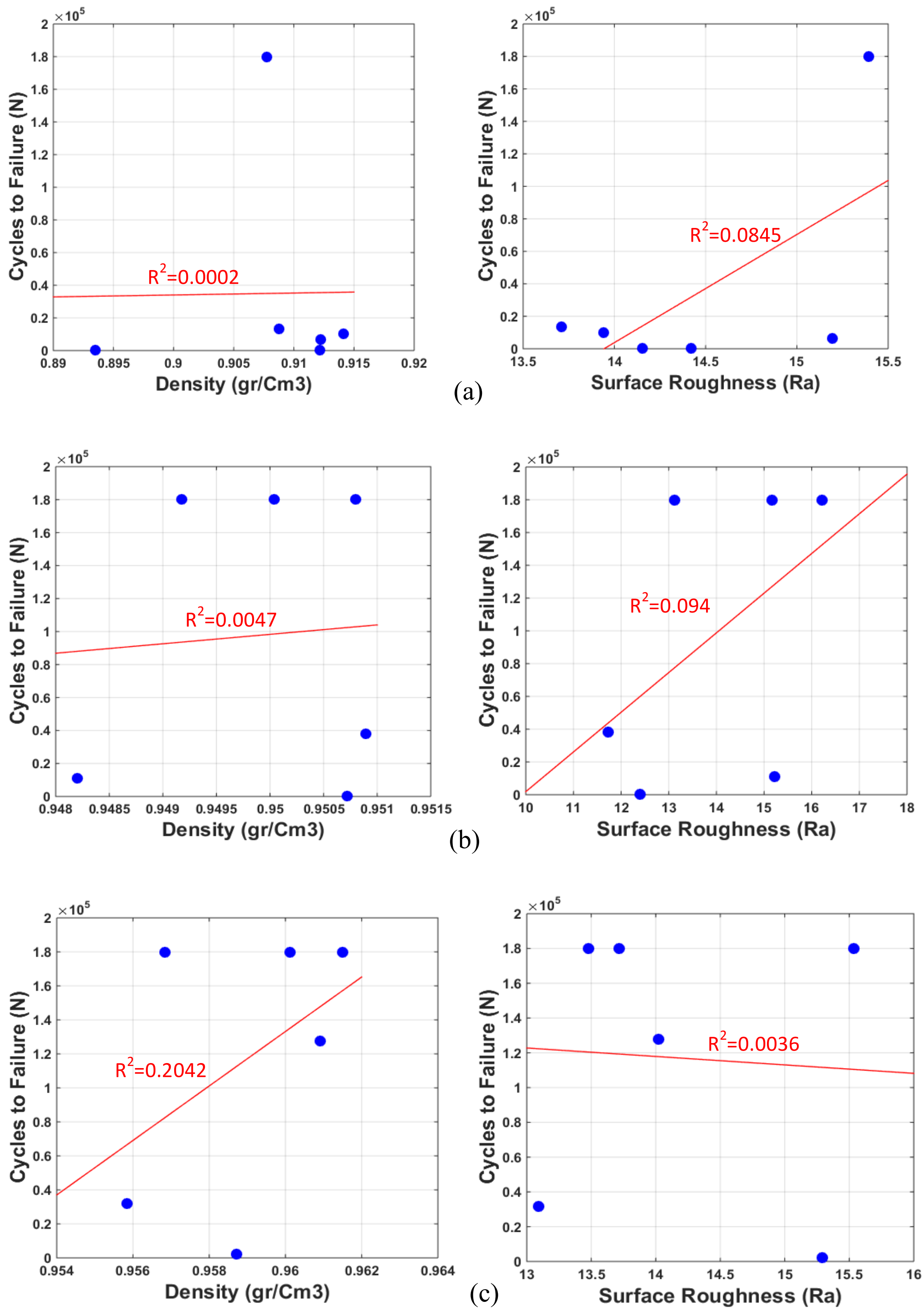


Figure 3- Density and surface roughness of a)2mm, b)4mm and c)6mm versus their fatigue life

3.2. Tension-Compression Excitation

Fatigue life of samples was also plotted for tension-compression tests, as shown in Figure 4, to investigate the effect of section thickness of the samples on their fatigue life at the two examined stress levels.

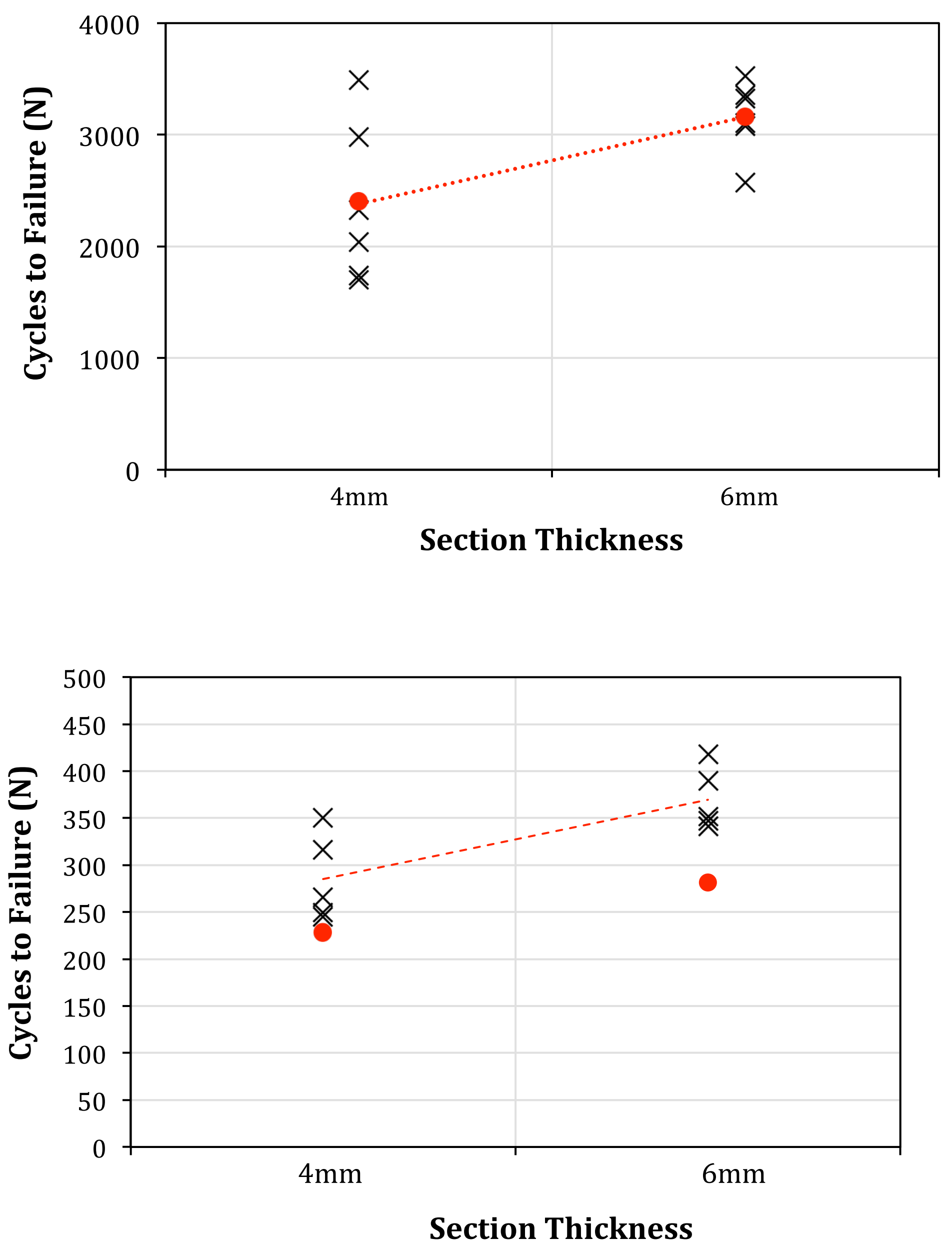


Figure 4 - Number of cycles vs. section thickness for stress levels of 20 MPa and 30 MPa

As can be observed from the figures, the number of cycles to failure of samples at the same stress level is in a similar range. However, it is clear that the number of cycles increases with section thickness in both stress levels.

Statistical analysis was performed on the results from both stress levels to evaluate the significance in the difference between the results for each stress level. The results from the Mann-Whitney U test revealed significant difference between fatigue life of samples of the two groups of section thickness (4mm section thickness; $U=6$, $p=0.032$ and 6mm section thickness; $U=2$, $p=0.028$). This means that fatigue life of LS Nylon 12 samples under tension-compression loading increases with section-thickness.

3.3. Hysteresis Loops

Hysteresis loops of the samples were produced for the both tension only and fully reversed loading conditions to study the energy and stiffness changes in parts with different section thicknesses.

Figure 5 shows hysteresis loops of 4mm and 6mm samples under tension-tension and tension-compression with maximum stress levels of 20MPa. Loops presented in these figures only show the first, middle and final cycles of each sample. The first cycle is the cycle after the sine-tapered period where the cyclic load grows to its peak values, and final cycle is the cycle where load levels drop and failure begins.

No significant change in the area inside the hysteresis loops, which represents the dissipated energy within the samples, can be observed in the tension only samples. However, the amount of dissipated energy increases substantially towards the final cycles within the tension-compression samples. The tension-compression hysteresis graphs also show that while both samples have similar amounts of dissipated energy in the first cycle, the difference in these values increases with the number of cycles.

The thicker sample shows a visibly larger amount of dissipated energy towards the final cycles.

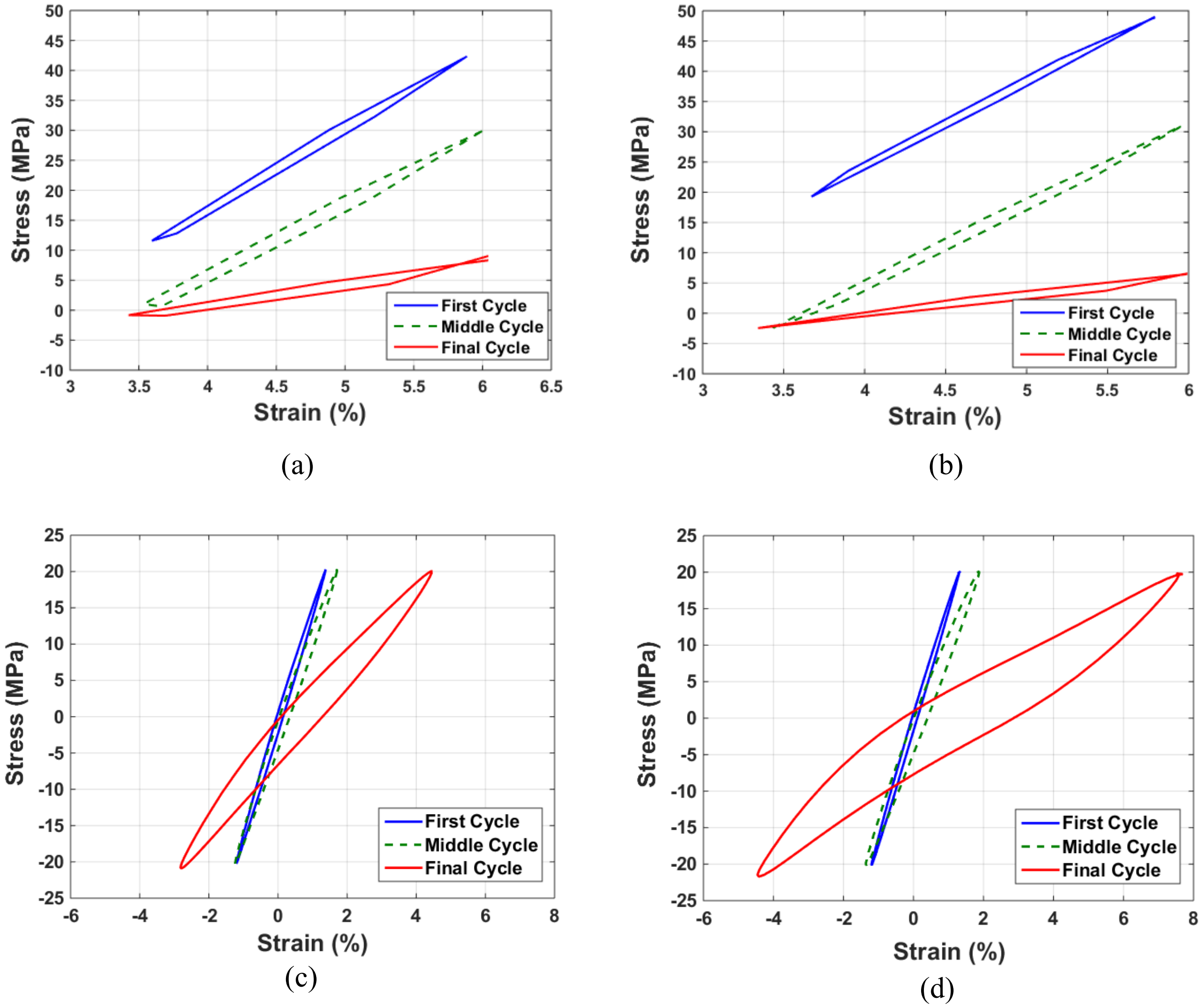
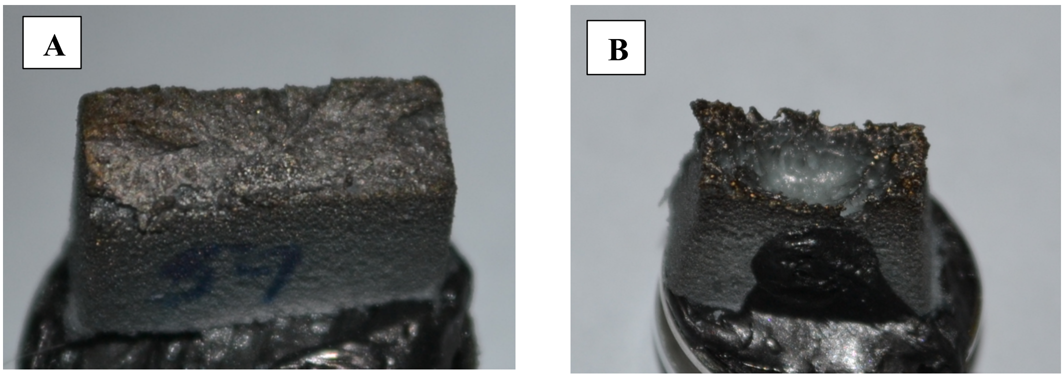


Figure 5- Hysteresis loops for 4mm and 6mm samples subject to a,b) tension-tension and c,d)tension-compression with 20MPa stress level loading respectively

Apart from dissipated energy, the slope of the hysteresis loops shows the stiffness of the material in each cycle. The slope of the loops in the tension only samples does not change up to the final cycles, which indicates brittle fracture of the samples. This shows that in specimens subject to tension-tension loading, failure of the specimen is controlled by the tensile strength, therefore the failure can start anywhere in the cross section. As a results section thickness of samples do not affect their fatigue life.

However, it is clearly visible that the slope of the hysteresis loops in both section thicknesses of the tension-compression samples decreases as the number of cycles increase, showing that the material is changing to a less stiff state. This can be associated with the fact that the dissipated energy causes the sample to heat up. As the temperature of the material increases to its glass transition region and possibly past that, the amorphous polymer chains soften, leading to lower stiffness and larger deformations at the same stress level.

The difference in fracture behaviour of parts under tension-tension and tension-compression loading can also be observed in the images from the fracture surface of broken samples in Figure 6. No sign of necking, which is a clear indication of ductile fracture or deformation in the loading direction, can be seen on fracture surface of the tension only sample (A and C). It is clear, however, that the tension-compression sample have experienced a ductile fracture dominated by shear stresses. Signs of plastic deformation and necking can be observed in images B and D.



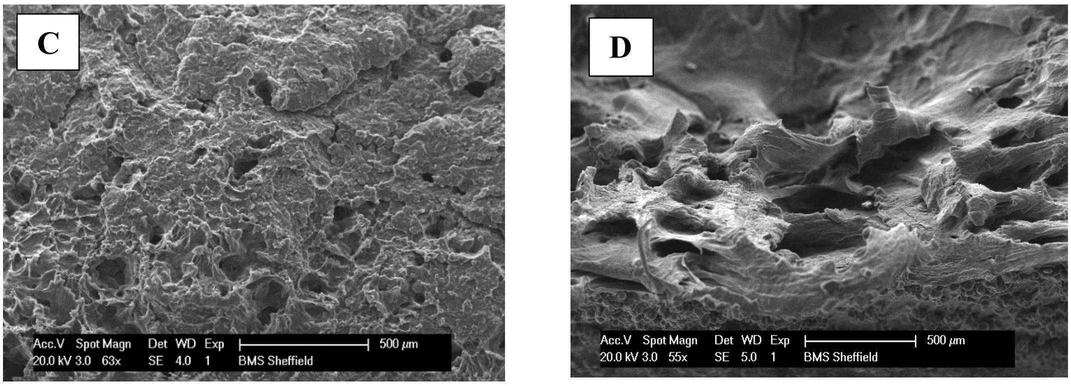


Figure 6- Fracture surface of samples broken under A,C)tension-tension and B,D)tension-compression cyclic loading

3.4. Thermal Analysis

As mentioned in section 2, surface temperature of the samples was measured during testing using an infrared camera. While temperature of tension only samples stayed stable throughout testing, temperature of the tension-compression samples increased rapidly up to the point of their fracture. Figure 7 shows the thermal history of a number of 4mm and 6mm samples subject to 20MPa and 30MPa stress level tension-compression loading.

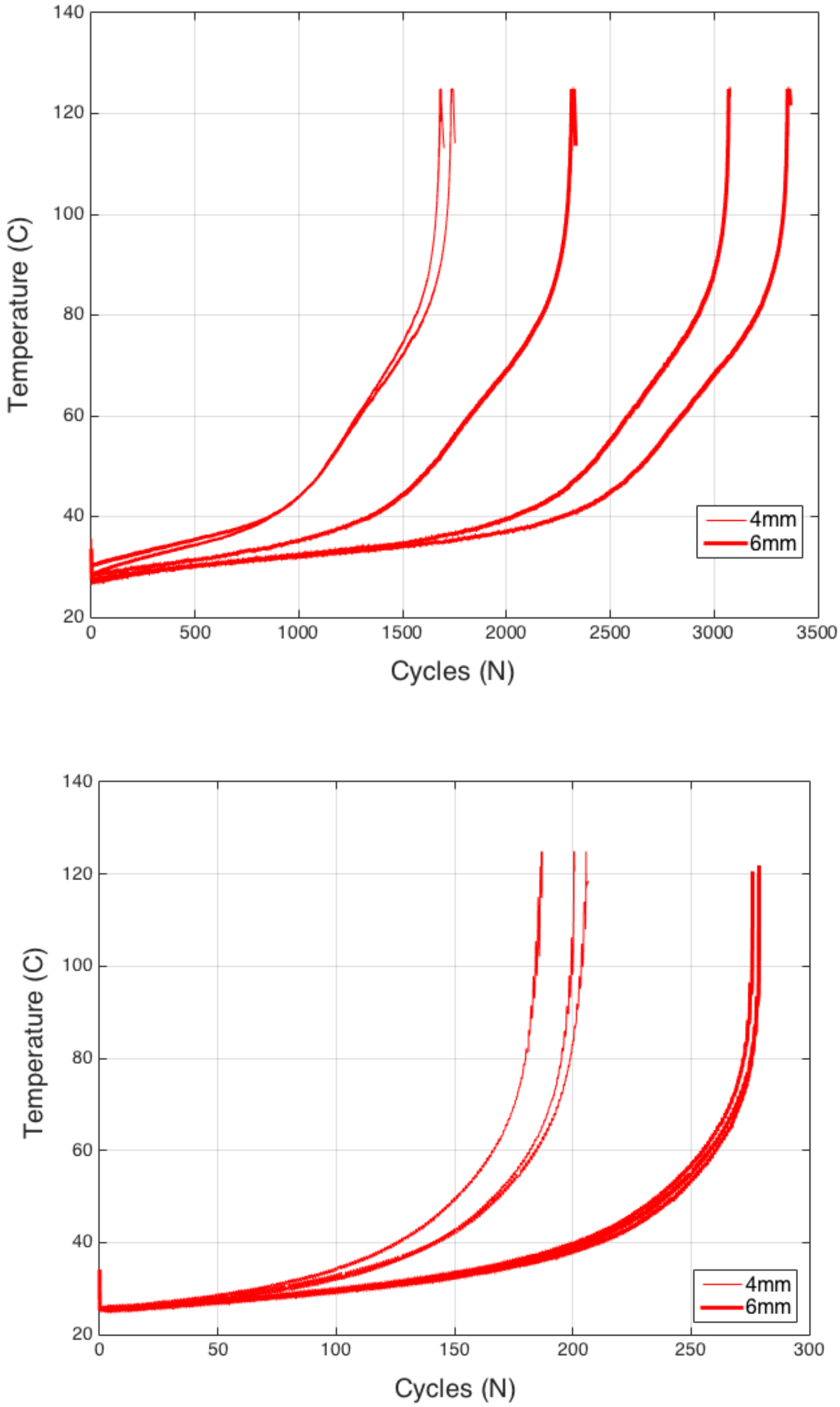


Figure 7- Thermal history of 4mm and 6mm samples under 20MPa and 30MPa stress levels

One of the inconsistencies observed in the results from the hysteresis loops and the temperature histories of the samples, is that while the thicker samples were shown to dissipate more energy in each cycle their heating rate is lower than the thinner samples. This could be associated to that fact that in compression, failure is instigated by buckling. Buckling load is proportional to the second moment of area (I) value, meaning that the thinner specimens experience larger amounts of buckling compared to the thicker ones which leads to faster increase in their surface temperature. Even a small amount of buckling, which does not have to be particularly visible, will generate additional strains causing the surface temperature to increase and the material to soften. However, the thicker samples would have larger heat transferred to their core at the failure point hence larger hysteresis loops, due to their longer fatigue life.

It can also be observed that in all of the plots, temperature rises linearly at first, up to around 35°C. After this temperature, thermal behaviour of the samples changes under different stress levels, while it is similar for different section thicknesses with the same stress level. Once the maximum temperature in a sample hits the T_g range (~53°C), all samples in the same stress level fail within similar number of cycles. This is more certain in the higher stress level.

The reason for this behaviour of the samples can be explained as follows. At the start of testing, amorphous chain segments of the polymer are frozen in fixed positions with their segments vibrating around these fixed positions. Thermal energy at this temperature is not large enough to overcome the potential barriers for larger motions of these segments of the polymer. As the temperature starts to increase, and reaches the glass transition temperature, the amplitude of vibrational motion increases, and eventually the thermal energy becomes large enough to overcome the potential energy barriers to segment rotation and translation. This leads to softening of the amorphous polymers chains, hence fall in elastic modulus and as a result, larger deformation of the sample under the same load. Larger deformations cause more friction between the chains; therefore larger temperature rise in the sample. This phenomenon continues and accelerates itself until rupture of the sample occurs.

Although samples showed different behaviours under different stress levels and besides their different number of cycles to failure, it is clear from Figures 7 that all of the samples have broken in the same temperature range. Thermal history plots in these figures indicate that once the sample got to a temperature range of 120-125°C all samples have failed no matter their size and stress level.

4. Conclusion

In this study, laser sintered nylon 12 parts with different section-thicknesses were subjected to tension-tension and tension-compression loading to investigate the effect of section-thickness on their fatigue behaviour. Tension-tension tests were performed as displacement controlled and tension-compression tests were performed as force-controlled to avoid the buckling caused by cyclic creep of samples under displacement-controlled loading.

It can be concluded from the results presented that section-thickness of the parts has no apparent influence on their displacement-controlled tension-only fatigue life. Although a slight increase was visible in their fatigue life with increase of section thickness, statistical analysis showed that the amount of increase was negligible.

Results for parts subjected to force-controlled fully-reversed loading showed an increase in their fatigue life with their section-thickness. The increase was also shown to be significant in statistical analysis, as a result it can be concluded that fatigue life of LS Nylon 12 parts subject to tension-compression loading increase with their section-thickness.

It was concluded from the thermal history plots of the samples that in tension-compression because of the small amount of buckling samples experience in each cycle, their surface temperature increase. As thinner samples have larger buckling under the same loading, a more rapid increase is visible in their surface temperature and as they have a smaller fatigue life compared to thicker samples. It was also shown that regardless of their thickness, parts experience brittle mechanical failure under tension-only loading due to their UTS dominant behaviour and ductile thermal failure under fully reversed loading due to their buckling-thermal dominant behaviour.

References

[1] B. Caulfield, P. E. McHugh, and S. Lohfeld, "Dependence of mechanical properties of polyamide components on build parameters in the SLS process," *J. Mater. Process. Technol.*, vol. 182, no. 1–3, pp. 477–488, Feb. 2007.

[2] H. C. . Ho, I. Gibson, and W. . Cheung, "Effects of energy density on morphology and properties of selective laser sintered polycarbonate," *J. Mater. Process. Technol.*, vol. 89–90, pp. 204–210, May 1999.

[3] U. Ajoku, N. Hopkinson, and M. Caine, "Experimental measurement and finite element modelling of the compressive properties of laser sintered Nylon-12," *Mater. Sci. Eng. A*, vol. 428, no. 1–2, pp. 211–216, Jul. 2006.

[4] T. L. Starr, T. J. Gornet, and J. S. Usher, "The effect of process conditions on

mechanical properties of laser-sintered nylon," *Rapid Prototyp. J.*, vol. 17, no. 6, pp. 418–423, 2011.

[5] M. Blattmeier, G. Witt, J. Wortberg, J. Eggert, and J. Toepker, "Influence of surface characteristics on fatigue behaviour of laser sintered plastics," *Rapid Prototyp. J.*, vol. 18, no. 2, pp. 161–171, 2012.

[6] B. Van Hooreweder, F. De Coninck, D. Moens, R. Boonen, and P. Sas, "Microstructural characterization of SLS-PA12 specimens under dynamic tension/compression excitation," *Polym. Test.*, vol. 29, no. 3, pp. 319–326, May 2010.

[7] H. Amel, H. Moztarzadeh, J. Rongong, and N. Hopkinson, "Investigating the behavior of laser-sintered Nylon 12 parts subject to dynamic loading," *J. Mater. Res.*, vol. 29, no. 17, pp. 1852–1858, 2014.

[8] B. Van Hooreweder, D. Moens, R. Boonen, J.-P. Kruth, and P. Sas, "On the difference in material structure and fatigue properties of nylon specimens produced by injection molding and selective laser sintering," *Polym. Test.*, vol. 32, no. 5, pp. 972–981, Aug. 2013.

[9] J. a. Sauer, E. Foden, and D. R. Morrow, "Influence of molecular weight on fatigue behavior of polyethylene and polystyrene," *Polym. Eng. Sci.*, vol. 17, no. 4, pp. 246–250, 1977.

[10] J. Sauer and M. Hara, "Effect of molecular variables on crazing and fatigue of polymers," *Crazing Polym. Vol. 2*, 1990.

[11] L. Pruitt and L. Bailey, "Factors affecting near-threshold fatigue crack propagation behaviour of UHMWPE.pdf," *Polymer (Guildf).*, vol. 39, no. 8–9, 1998.

[12] H. Zarringhalam, N. Hopkinson, N. F. Kamperman, and J. J. de Vlieger, “Effects of processing on microstructure and properties of SLS Nylon 12,” *Mater. Sci. Eng. A*, vol. 435–436, pp. 172–180, Nov. 2006.

[13] C. Majewski and N. Hopkinson, “Effect of section thickness and build orientation on tensile properties and material characteristics of laser sintered nylon-12 parts,” *Rapid Prototyp. J.*, vol. 17, no. 3, pp. 176–180, 2011.